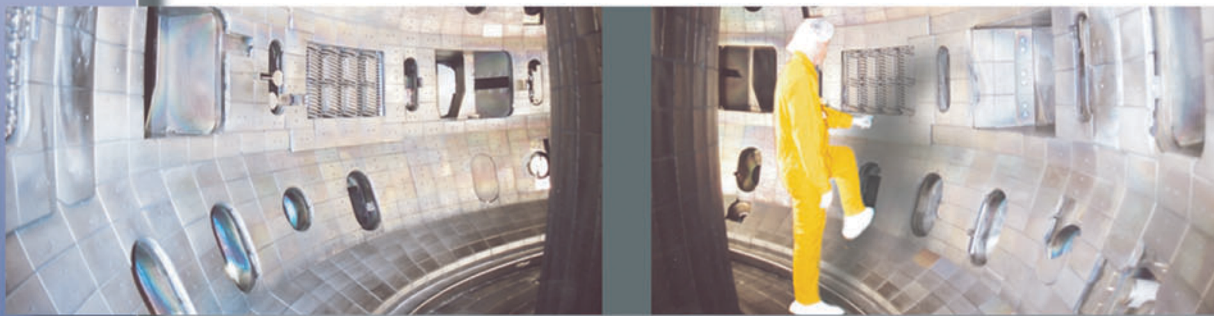
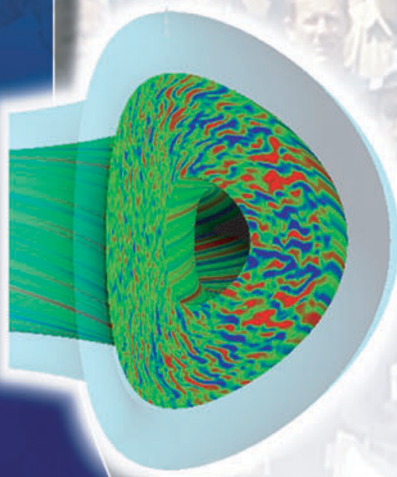




University Research and DIII–D

by
G.A. Navratil

Presented at
Office of Fusion Energy Science
FY07 Budget Planning Meeting
Washington, DC

March 15–16, 2005

032-05/GAN/rs

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

GENERAL ATOMICS

DIII–D SUPPORTS A HUGE INTERNATIONAL PROGRAM

- 90 institutions participate
- 425 active users
- 317 scientific authors
- Students and faculty from
  - 65 universities
  - 28 states

US Universities

Auburn (Auburn, Alabama)
Colorado School of Mines (Golden, CO)
Columbia (New York, NY)
Georgia Tech (Atlanta, GA)
Hampton (Hampton, VA)
Lehigh (Bethlehem, PA)
Maryland (College Park, MD)
Mesa College (San Diego, CA)
MIT (Boston, MA)
Palomar (San Marcos, CA)
New York U. (New York, NY)
SDSU (San Diego, CA)
Texas (Austin, TX)
UCB (Berkeley, CA)
UCI (Irvine, CA)
UCLA (Los Angeles, CA)
UCSD (San Diego, CA)
U. New Mexico (Albuquerque, NM)
U. Rochester (NY)
U. Utah (Salt Lake City, UT)
Washington (Seattle, WA)
Wisconsin (Madison, WI)

US Labs

ANL (Argonne, IL)
LANL (Los Alamos, NM)
LBNL (Berkeley, CA)
LLNL (Livermore, CA)
ORNL (Oak Ridge, TN)
PPPL (Princeton, NJ)
SNL (Sandia, NM)

Industries

Calabasas Creek (CA)
CompX (Del Mar, CA)
CPI (Palo Alto, CA)
Digital Finetec (Ventura,
DRS (Dallas, TX)
DTI (Bedford, MA)
FAR Tech (San Diego, C
IOS (Torrance, CA)
Lodestar (Boulder, CO)
SAIC (La Jolla, CA)
Spinner (Germany)
Tech-X (Boulder, CO)
Thermacore (Lancaster,
Tomlab (Willow Creek, C
TSI Research (Solana Be

Russia

Ioffe (St. Petersburg)
Keldysh (Udmurtia, Moscow)
Kurchatov (Moscow)
Moscow State (Moscow)
St. Petersburg State Poly (St. Petersburg)
Triniti (Troitsk)
Inst. of Applied Physics (Nizhny Novgorod)

European Community

Cadarache (St. Paul-lez, Durance, France)
Chalmers U. (Goteberg, Sweden)
CFN-IST (Lisbon, Portugal)
CIEMAT (Madrid, Spain)
Consorzia RFX (Padua, Italy)
Culham (Culham, Oxfordshire, England)
EFDA-NET (Garching, Germany)
Frascati (Frascati, Lazio, Italy)
FOM (Utrecht, The Netherlands)
Helsinki U. (Helsinki, Finland)
IFP-CNdR (Italy)
IPP (Garching, Greifswald, Germany)
ITER (Garching, Germany)
JET-EFDA (Oxfordshire, England)
KFA (Julich, Germany)
Kharkov IPT, (Ukraine)
Lausanne (Lausanne, Switzerland)
IPP (Greifswald, Germany)
RFX (Padova, Italy)
U. Dusseldorf (Germany)
U. Naples (Italy)
U. Padova (Italy)
U. Strathclyde (Glasgow, Scotland)

Japan

JAERI (Naka, Ibaraki-ken, Japan)
JT-60U
JFT-2M
Tsukuba University (Tsukuba, Japan)
NIFS (Toki, Gifu-ken, Japan)
LHD

Other International

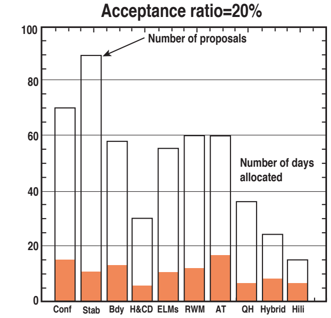
Australia National U. (Canberra, AU)
ASIPP (Hefei, China)
Dong Hau U. (Taiwan)
KBSI (Daegon, S. Korea)
KAERI (Daegon, S. Korea)
Nat. Nucl. Ctr. (Kurchatov City, Kazakhstan)
Pohang U. (S. Korea)
Seoul Nat. U. (S. Korea)
SWIP (Chengdu, China)
U. Alberta (Alberta, Canada)
U. of Kiel (Kiel, Germany)
U. Toronto (Toronto, Canada)

STRONG INTERNATIONAL INTEREST IS SHOWN IN THE 451 RESEARCH PROPOSALS FOR 2004

FOREIGN	
Belgium	1
France	4
Germany	8
JET	3
Portugal	3
Spain	2
Italy	1
Switzerland	3
Russia	3
Japan	2
Australia	1
England	7
Canada	4
Total:	42

DOMESTIC	
Columbia	29
FarTech	2
GA	183
Lehigh	2
LLNL	23
NRL	1
MIT	3
ORNL	43
PPPL	66
SNL	9
UCI	2
UCLA	17
UCSD	18
U. Texas	4
U. Wisconsin	6
Unaffiliated	1
Total:	409

Acceptance ratio=20%



Research Topic

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

DIII–D AS A NATIONAL SCIENCE FACILITY: UNIVERSITY PERSPECTIVE

- In many fields of science "National Facilities" play a critical role
  — (e.g. SLAC, RHIC, SNS, LIGO, NSLS, ...)
- Large enough: to produce experimental conditions for frontier science advances
- Large enough: to support a "critical mass" of research groups working together
- Distinguishing feature: focal point for national expertise and capability
  — Synergy of broad and diverse national involvement leads to significant discovery – transcends capability of any single (or a few) institutions
- The DIII–D National Fusion Facility plays that role for burning plasma and advanced tokamak physics in the United States

MAJOR UNIVERSITY PROGRAMS ON DIII–D

• Columbia U.	Resistive wall mode research
• GeorgiaTech	Pedestal and edge physics
• MIT	Phase contrast imaging diagnostic
• UC-Irvine	Energetic particle physics
• UCLA	Turbulence measurements, transport
• UCSD	Edge turbulence measurements, disruptions
• U. Maryland	EC diagnostics
• U. Texas	ECE measurements, confinement physics
• U. Toronto	Divertor physics
• U. Wisconsin	BES, turbulence and transport

MAJOR UNIVERSITY PROGRAMS ON DIII–D

Plasma Turbulence Measurements

Columbia U.	Resistive wall mode research
GeorgiaTech	Pedestal and edge physics
MIT	Phase contrast imaging diagnostic
UC-Irvine	Energetic particle physics
UCLA	Turbulence measurements, transport
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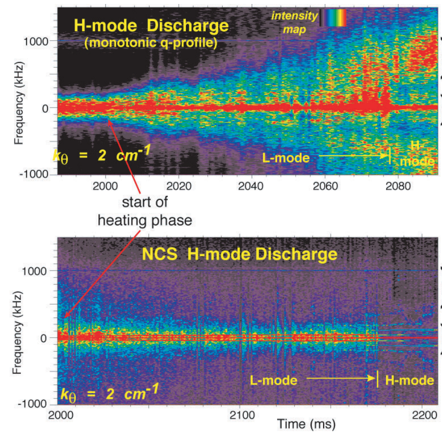
ALL DIII–D TURBULENCE MEASUREMENTS ARE CARRIED OUT BY UNIVERSITY COLLABORATIONS

- **FIR scattering – UCLA**
  - Survey instrument covering entire plasma radius
  - Good time and wavenumber resolution



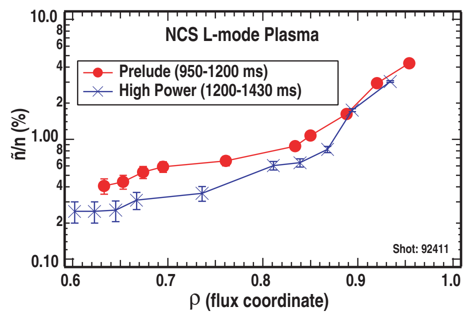
FIR scattering data

L– and H–mode

NCS L– and H–mode

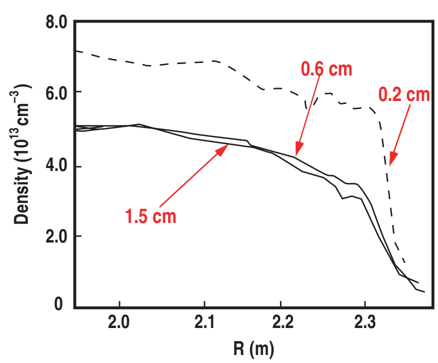
- **Phase contrast imaging – MIT**
  - Ability to measure long wavelength fluctuations

- **BES (Beam Emission Spectroscopy) – U. Wisc.**
  - Spatially resolved with ability to provide profiles
  - Absolute measurement of turbulence levels



Turbulence level from BES system

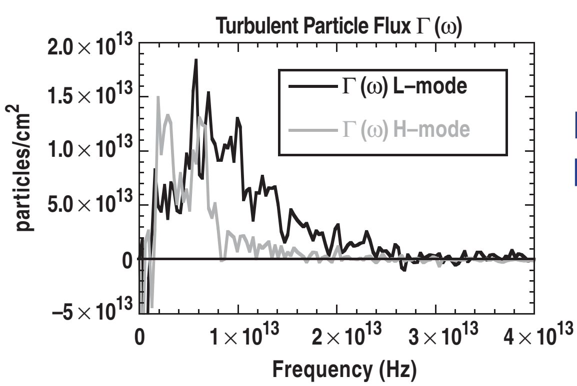
- **Reflectometry – UCLA**
  - Radial correlation length of the turbulence
  - Relative ñ with high spatial and temporal resolution



Correlation length from reflectometer

- **Electron cyclotron emission – U. Texas/U. Maryland**
  - Electron temperature fluctuations

- **Fast edge probes – UCSD**
  - Localized edge turbulence



Edge probe

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MAJOR UNIVERSITY PROGRAMS ON DIII–D

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COLUMBIA PART OF RWM "TEAM" ON DIII–D

- History: M. Mauel (94-95) and G. Navratil (95-96) spent back-to-back sabbatical leaves at DIII–D to establish basis for collaboration
  - Mauel: RWM rotation studies early NBI led to discovery of NCS
  - Lazarus and Navratil: used NCS in DIII–D for high QDD with neoclassical ions
- 1996 MOU for CU/DIII–D collaboration on RWM passive and active control
- 1997 PPPL joins DIII–D RWM and funds new RWM control amplifiers
- Combination of onsite personnel (1 initially, now 2), plus sabbatical leaves Mauel (94-95); Navratil (95-96; 01-02) allows us to share leadership of RWM Research (Thrust 4): CU/PPPL/GA core RWM group
- RWM research on DIII–D has led to significant discoveries and advances in physics basis of RWM control by rotation and feedback:
  - 2000 – Active feedback control demonstrated
  - 2001 – Discovery of "Resonant Field Amplification" and effect on toroidal plasma rotation

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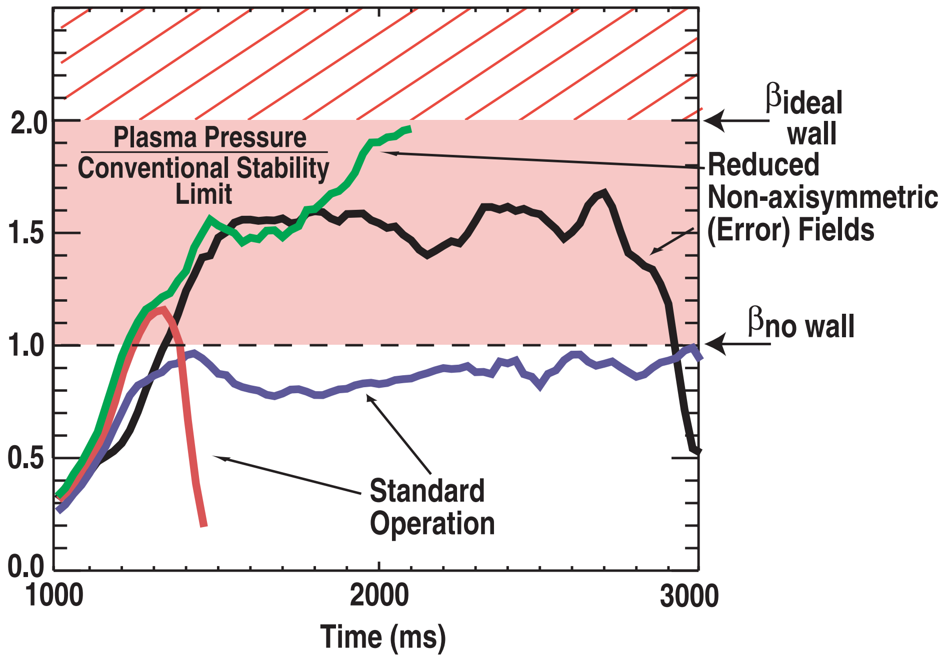
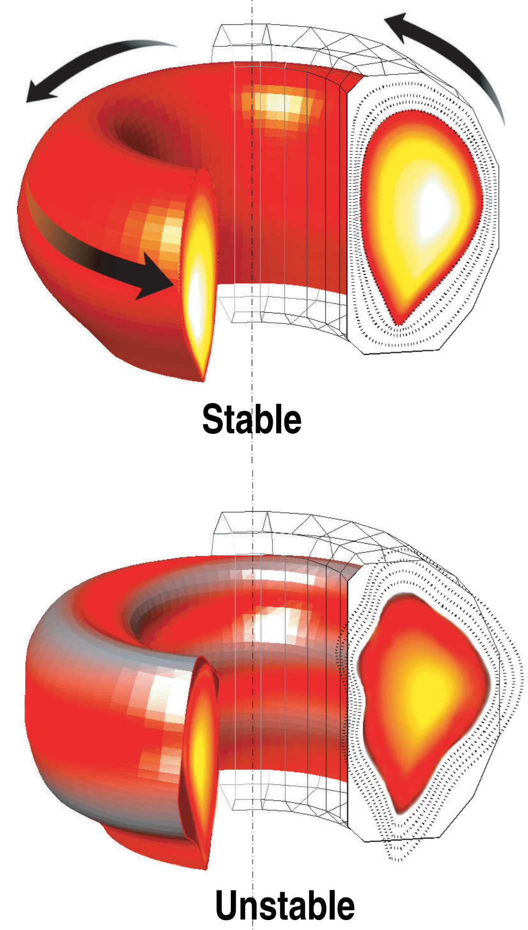
MAJOR BREAKTHROUGH IN 2001
RWM STABILIZED BY ROTATION TO IDEAL LIMIT

- **Spinning plasma improves prospects for fusion energy**
  — Washington Post, Physics Today, New Scientist, San Diego Union-Tribune





- $\beta_N > \beta_N^{\text{no wall}}$
- $\beta_N \sim \beta_N^{\text{ideal wall}}$
- Team effort: GA, Columbia, PPPL

⇒ **Future plans: exploitation β, $\beta_N \uparrow$ through rotation and active feedback (I–coil)**

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BASIC PHYSICS OF THE WALL STABILIZED KINK MODE HAS BEEN ESTABLISHED*

- Dissipation (viscosity) models in MARS give qualitative agreement with experiment for critical rotation thresholds
- Resonant field amplification critical for RWM dynamics since $\omega \sim 0 \Rightarrow$ can slow rotationally stablized plasma near marginal stability and error field reduction allows ideal limit stabilization by rotation
- Qualitative agreement with kinetic damping models BUT complete quantitative details still not complete: predicted γ and ω not self-consistent with experiment
- Rigid mode model is a useful tool for analysis

*G.A. Navratil, "Control of External Kink Instability," APS-DPP 2004 Review Talk

DESIGN TOOLS AND PREDICTIVE PHYSICAL MODEL IN HAND FOR KINK MODE CONTROL IN BURNING PLASMA EXPERIMENTS

- Can these slowed growth rates kinks be stabilized by active feedback control? YES!
  - Feedback stabilization of the RWM has been demonstrated significantly above the no-wall pressure limits for 100 s of wall times
  - 2D MARS+F and 3D VALEN+DCON provide quantitative tools to design and assess optimized feedback control systems: coil location and geometry, feedback loop transfer function, and noise and power requirements

LEVERAGE OF UNIVERSITY/DIII–D COLLABORATION LEADS TO SIGNIFICANT BENEFIT TO BOTH AND TO NATIONAL PROGRAM

- Insight and tools developed at university are implemented using the resources of DIII–D National Facility
  - University brings more than just a pair of hands to national facility team – it brings independent ideas and perspective on frontier research questions and sets stage for discovery
  - Leads to important advances in understanding and often an expanded scope of inquiry (e.g. RWM I-coils also designed to allow ergotic edge experiments: may be key to ELM control in ITER)

- University home program strongly benefits: advances made as participant in a "world class experiment" provide insight and drive for new research questions and direction at on-campus activity both in experiment and theory
  - Graduate student PhD research is enormously enriched by immediate access to "important question areas" and resources provided by the national facility collaboration

UNIVERSITY RESEARCHERS ON DIII–D HAVE ACHIEVED NATIONAL RECOGNITION FOR IMPACT AND EXCELLENCE

- APS 2004 Excellence Prize to W.W. Heidbrink and L. Chen of UC-Irvine, C.Z. Cheng and K.L. Wong (PPPL), and E. Strait (GA) for TAE work

- APS 2001 Excellence Prize to E.J. Doyle of UCLA, K.H. Burrell and R.J. Groebner (GA), and E.D. Synakowski (PPPL) for E$\times$B shear stabilization of turbulence

- APS 1999 Excellence Prize to R.J. Fonck of U. Wisconsin, partially for BES work on DIII–D

- APS Fellows – 22 (out of 63 total)

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PROPOSED BUDGET CUTS IN FY06 DAMAGE UNIVERSITY PARTCIPATION IN DIII-D NATIONAL RESEARCH PROGRAM

	FY05	FY06	FY06(I)	FY07	FY07(I)
University budgets	$2,491K	$2,232K	$259K	$2,565K	$1,000K
University FTE	17.1	15.3	1.8	17.1	20

- Direct cut of 10% in university participation will produce disproportional response due to long time scale for PhD training and 2–3 years needed for an effective post-doctoral experience
- Coupled with substantial run-time reduction in overall DIII–D budget, effective collaboration will be seriously damaged; the investment made by the U.S. over many years in building up the DIII–D National Team will be jeopardized
- The "opportunity cost" of these reductions is very large in our effort to maintain key competencies in burning plasma physics and attract first-rate new scientists to the program who will be essential to provide the leadership and influence the U.S. needs to be effective on ITER
- Correspondingly a modest increase could significantly expand involvement as we prepare to attract and train the U.S. ITER team that will participate domestically or onsite in 2015 and beyond: e.g. ~20 new students involved for $1,000K

DIII–D'S SCIENTIFIC PRODUCTIVITY COULD SUPPORT MORE PH.D. THESES AND ENTRY POST-DOC RESEARCH

- Historically – 65 universities from 28 states
- 20 U.S. universities participate in DIII–D now
- DIII–D has trained
  - 31 graduate students
  - 26 post doctoral fellows
- Post-Doc's work lead to significant contribution (e.g. IAEA 2004)
  - W.M. Solomon (PPPL)
  - M. Groth (LLNL)
  - H. Reimerdes (Columbia)
  - E.M. Hollman (UCSD)

- DIII–D can train more young researchers for ITER and the fusion program
  - An additional $1 M per year could support 20 more students and post docs

NEAR TERM Ph.D THESES ON DIII–D

Ongoing Theses

1. A. McLean - U. Toronto – Migration of materials in the SOL and Divertor Plasmas

2. J. Dorris – MIT – Phase Contrast Imaging

3. N. Antoniuk – UCSD – Spectroscopy of Dalpha region for main ion Ti and internal B field

4. Y. Luo – UCI - Measurement of fast ion profiles using D-alpha spectra-- first data from this system this week.

5. Katsuro-Hopkins - Columbia U. - "Optimized Feedback Control System Modeling" -- includes realistic noise and amplifier bandwidth for design of DIII-D and ITER RWM control systems

6. M. Shafer and M. Schlossberg – Wisconsin - Determination of local heat flux in tokamak plasma-- combining BES and high speed CER measurements.

Theses Under Consideration

7. N. Pablant – UCSD - Determination of internal magnetic field in D III-D using Stark splitting of beam emission

8. N. Pablant – UCSD - Determination of internal field line pitch using amplitude ratio of Stark components

Theses That Could Be Done

9. Validation of the theory of electron-cyclotron current drive

10. Non-linear effects in electron cyclotron current drive at high power and plasma temperature.

11. Search for zonal flows and geodesic acoustic modes.

12. Scaling of turbulent diffusion with plasma beta

13. Spectroscopy of resistive wall modes

14. Stabilization of neoclassical tearing modes by electron cyclotron current drive.

15. Effect of stochastic magnetic field structures on edge localized modes in a tokamak.

16. Turbulent energy flows in k-space-- based on 2D turbulence imaging using BES

17. Investigation of NTM stability by MHD spectroscopy techniques (would use the I-coil in the 1-10 kHz range)

18. Physics of the penetration of a high-pressure impurity gas jet into a hot plasma

19. Tokamak equilibrium in a weakly non-axisymmetric magnetic field (i.e., plasma response to error fields)

20. Plasma rotation damping by resonant and non-resonant magnetic field perturbations (i.e., effect of error fields on rotation)

21. Equilibrium and stability of tokamak plasmas with near-zero central current density (i.e., current hole plasmas)

22. Angular momentum transport in neutral beam-heated plasmas

23. Effects of local current density profile on the m=1 kink instability (i.e., sawtooth modification by ECCD near the q=1 surface)

24. Transport studies with modulated ECH.

25. Coupled Te and Ti perturbation analysis tool to study modulated ECH transport experiments

26. Scenario modeling of AT plasmas for ITER

27. Experimental study of the impact of intermediate and high-k turbulence on plasma transport - further develop existing diagnostics to improve measurements and correlate measurements with transport

28. Density fluctuation studies with high time resolution CO2 multi-chord interferometer - our newly upgraded system has seen TAE, CAE etc. modes

29. Develop a new Thomson Scattering system capable of 2D measurements - plasma lies within the laser cavity, 2D measurements by multiple passes through the plasma - Q-switch or CW operation may be possible

30. Development and application of a fast ion diagnostic for studies of absorption of fast waves by energetic beam ions, testing new theory and modeling

31. Analysis of modulated ECH/ECCD experiments; develop a coupled two-fluid approach to the modulated transport equations

32. Study of poloidal flux diffusion and noninductive currents in DIII-D, using the time-derivative of the Grad-Shafranov equation

33. Study nonlinear effects of ECCD on rational flux surfaces or at low density, and effects of transport on current drive profile

34. Experimental study of bootstrap and resistivity models

35. Experimental study of nonlinear dissipation mechanisms for ICRF waves, including parametric decay and edge sheath dissipation

36. Study of breakdown mechanisms in an ICRF antenna (high relevance to ITER)

37. Interferometry using fast Alfven waves

38. Study of plasma loading of fast wave antennas in DIII-D and extensive comparison to models.

39. Measurement of ICRF waves with PCI diagnostic and compare with full-wave codes.

40. Experimental test of fast ion effects on sawteeth and comparison with models

41. Resistive interchange stability of AT experiments

42. Studies of tearing modes, BES/ECE/MSE/reflectometer imaging of the island itself.

43. Development of model-based control schemes for AT plasmas

44. L-H transition dependence on electron and ion heating.

45. Separating the role of magnetic shear, temperature ratio, and bulk rotation on energy transport

46. Alfven wave current drive

47. Development of maximum entropy approach to equilibrium reconstruction for optimal stability analysis